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REFERENCE

RESEARCH MEMORANDUM

for the

...Materiel Command, Army Air Forces

...NG INVESTIGATION OF THE R-2800-21 ...

IN THE P-47G AIRPLANE

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... Michael F. Valerino, and Eugene J. Ma...

...raft Engine Research Laboratory
Cleveland, Ohio

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

for the

Air Materiel Command, Army Air Forces

ALTITUDE COOLING INVESTIGATION OF THE R-2800-21 ENGINE IN THE P-47G AIRPLANE

III - INDIVIDUAL-CYLINDER TEMPERATURE REDUCTION BY MEANS OF INTAKE-PIPE THROTTLE AND BY COOLANT INJECTION

By E. Barton Bell, Michael F. Valerino
and Eugene J. Manganiello

SUMMARY

Flight tests were conducted on an R-2800-21 engine in the P-47G airplane to determine the effect on the wall temperatures of cylinder 10 of throttling the charge in the intake pipe and of injecting a water-ethanol coolant into the intake pipe. Cylinder 10 was chosen for this investigation because it runs abnormally hot (head temperatures of the order of 45° F higher than those of the next hottest cylinder) at the medium and high-power conditions.

Tests with interchanged cylinders showed that the excessive temperatures of cylinder 10 were inherent in the cylinder location and were not due to the mechanical condition of the cylinder assembly.

Other test results indicated that for the normal rated conditions of engine speed and manifold pressure, the head temperature of cylinder 10 could be reduced 90° F by intake-pipe throttling with an accompanying loss of 60 brake horsepower and up to 120° F by intake-pipe coolant injection with a loss of 30 brake horsepower. For operation at temperature-limited conditions, however, a gain in power output could have been realized by the use of either method.

The use of the intake-pipe throttle permitted a military power climb to be made to an altitude of 30,000 feet under conditions that would have otherwise been temperature-limited.

Throttling the charge in the intake pipe is a simpler method than coolant injection into the intake pipe particularly when only one cylinder is considerably hotter than any other. Coolant injection into the individual cylinders is a more efficient method than throttling in the intake pipe and is warranted when several cylinders are to be cooled or when parts of the complex equipment required are already available.

INTRODUCTION

At the request of the Air Materiel Command, Army Air Forces, the NACA Cleveland laboratory is conducting a cooling investigation of the R-2800 engine. As a part of this investigation, flight tests were made with the R-2800-21 engine in the P-47G airplane for variable engine and flight operating conditions at altitudes ranging from 5000 to 35,000 feet. An analysis of the engine-cooling test data to determine the effect of altitude cooling-air conditions on the engine-cooling characteristics is given in reference 1.

A study of the temperature distribution among the 18 cylinders (reference 2) shows that, for engine power outputs in excess of about 1100 horsepower, the head temperature of cylinder 10 may be more than 100° F higher than the average head temperature of the 18 cylinders and about 45° F higher than that of the next hottest cylinder. Two methods for reducing the temperature of cylinder 10 were accordingly applied and flight-tested; (1) throttling the charge in the cylinder-intake pipe by means of a butterfly valve, and (2) injection of coolant into the cylinder-intake pipe. These methods were not intended to correct the fundamental defects but were considered possible expedients for reducing the temperature of a predominantly hot cylinder regardless of the cause. An analysis presented in reference 3 shows the advantages of cooling only the overheated cylinders of an aircraft engine.

The effect of various positions of the intake-pipe throttle on the wall temperatures of cylinder 10 and on the engine power output and fuel consumption was determined in level flight at normal rated power. The effect of the throttle set at one fixed position on temperature and performance was also investigated in a military power climb.

The effect of various rates of internal-coolant flow on the wall temperatures of cylinder 10 and on the engine power output and fuel consumption was determined in level flight at normal rated power. Data were also obtained at one internal-coolant-flow rate in level flight at military power.

In order to check the possibility that the condition of the cylinder assembly might be contributing to the excessive temperatures, tests were conducted with cylinders 10 and 18 interchanged.

TEST EQUIPMENT AND PROCEDURE

Airplane and engine. - The flight tests were conducted on an R-2800-21 engine installation in a P-47G airplane. The R-2800-21 engine is an 18-cylinder, twin-row radial, air-cooled engine with a military rating of 2000 brake horsepower at an engine speed of 2700 rpm and a normal rating of 1625 brake horsepower at an engine speed of 2550 rpm. The supercharger equipment consists of an engine-stage blower with an impeller diameter of 11 inches and a gear ratio of 7.6:1 and a General Electric type C-1 turbosupercharger. The engine is equipped with a Bendix-Stromberg PT-13G1 injection-type carburetor, which meters the fuel to the inlet of the engine-stage blower. A controllable Curtiss Electric four-blade propeller (blade drawing No. 714-1C2-12) having a diameter of 12 feet, 2 inches and fitted with shank cuffs was used.

Instrumentation. - Cylinder-wall temperatures were measured by means of iron-constantan thermocouples and recording galvanometers, as described in detail in reference 2. The thermocouple locations on each engine cylinder are shown in figure 1. Thermocouple T12 was a standard rear-spark-plug-gasket type thermocouple; T35 was embedded about one-sixteenth inch in the metal of the rear spark-plug boss; T19 was embedded about one-sixteenth inch in the head metal at the base of the middle-head circumferential fin at the rear of the cylinder; T6 was embedded in the metal of the aluminum barrel muff about two-thirds of the way up the rear of the barrel finning; T14 was spot-welded to the rear of the cylinder barrel just above the hold-down flange. The absolute accuracy of the temperature values as measured by the thermocouples and recording galvanometer system was about $\pm 7^{\circ}$ F. The free-air temperature was obtained from the temperature reading of a calibrated resistance bulb thermometer installed under and near the tip of the right wing.

Engine speed was indicated on a sensitive tachometer and brake horsepower was determined by a conventional Pratt & Whitney hydraulic torquemeter. The values of fuel flow used in determining brake specific fuel consumption were obtained from indications of a deflecting-vane-type remote indicating fuel flowmeter. Manifold pressure was measured with standard aircraft equipment for the level flights and continuously recorded by an NACA flight instrument during the climb flights. Free-stream impact pressure was measured by a shrouded total-head tube installed on a streamline boom on the right wing tip. A swiveling static-pressure tube, which was calibrated in a special flight, was also installed on the boom about 1-chord length ahead of the leading edge of the wing. Continuous records of both the impact and static pressures were taken by NACA pressure recorders.

Cylinder interchange. - For the test using interchanged cylinders, cylinder 18 was chosen for interchange with cylinder 10 because it was a front-row cylinder and its temperature generally ran about engine average temperature. The cylinder interchange also included pistons, rings, and valves.

Intake-pipe throttle of cylinder 10. - The throttle mounted in the intake pipe of cylinder 10 and the five positions tested are shown in figure 2. The throttle consisted of an adjustable butterfly valve that could be locked in position. The shape of the butterfly valve was such that it was impossible to close fully the intake pipe. As the adjustment to the intake-pipe throttle had to be made on the ground, five separate flights, each with a different throttle setting, were made during which the outside air temperature varied $\pm 3^{\circ}$ F and the altitude was held at 10,080 ±40 feet. These tests were made at the normal rated engine speed and manifold pressure of 2550 rpm and 42.5 inches of mercury absolute, respectively. Cowl flaps were set "closed" for each of these tests. During each test, temperatures and engine conditions were recorded after stabilization.

Additional tests were made in climb without the intake-pipe throttle in cylinder 10 and with the throttle set at position 4 (fig. 2). The climb tests were made at military power conditions as follows: engine speed, 2700 rpm; manifold pressure, approximately 52 inches of mercury absolute; cowl-flap setting, wide open; mixture setting, automatic rich; and indicated airspeed, approximately 167 miles per hour. During these climb tests a continuous time history was obtained of pressure altitude, temperature of cylinder 10, free-air temperature, cooling-air pressure drop, impact pressure, manifold pressure, engine-torque pressure, and engine speed.

Coolant injection to cylinder 10. - A diagrammatic sketch of the coolant-injection system used in the tests is presented in figure 3. The internal coolant, 50 percent water and 50 percent ethanol by volume, was carried in a 5-gallon tank and was pumped to cylinder 10 by an electrically driven coolant pump. The flow was manually controlled with a needle valve and was indicated by an electrical differential-pressure transmitter and gage that measured the pressure drop of the coolant flow through a calibrated 3/64-inch diameter, thin-plate orifice. The coolant was injected into the intake pipe just ahead of the cylinder port through a primer nozzle with a No. 60 drilled hole in the outlet.

One flight was made at normal rated engine conditions (engine speed of 2550 rpm and manifold pressure of approximately 42.5 in. Hg) wherein five test points were taken with internal-coolant flows of 0, 13.5, 26, 43.5, and 0 pounds per hour. Cowl flaps were set "closed." Another flight was made at military rated engine conditions (engine speed of 2700 rpm and manifold pressure of 52 in. Hg) during which runs were made with internal-coolant flows of 0, 55, and 0 pounds per hour. Both flights were made at a pressure altitude of 5000 feet. Engine temperatures and engine conditions were recorded after stabilization for each test.

RESULTS AND DISCUSSION

Cylinder-interchange test. - A comparison of the engine temperature distribution before and after interchanging cylinders 10 and 18 is shown in figure 4. The temperature pattern obtained in the flight with the interchanged cylinders is compared with that of a flight made several months previously with the cylinders in the original position. As can be seen in figure 4, the temperature pattern was not appreciably altered by interchanging cylinders 10 and 13. This result is considered conclusive proof that the excessive temperatures of cylinder 10 are not due to the mechanical condition of that particular cylinder assembly but are inherent in the position of cylinder 10 in the engine.

Tests with intake-pipe throttle. - The effect of the intake-pipe throttle on the wall temperatures of cylinder 10 is shown in figure 5. The spark-plug-gasket temperature T12 and the spark-plug-boss temperature T35 were reduced almost 90° F by closing the intake-pipe throttle to position 4. The temperature at the rear middle of the cylinder head T19 was reduced only about 75° F. The average temperature (at the location of T19) of all of the cylinders except 10 is shown as an indication of the effects of unavoidable changes in engine and atmospheric conditions on the cylinder temperature. The cylinder-barrel temperatures T6 and T14 were also cooled by the intake-pipe throttle but only about one-half or one-third as much as the head temperatures.

When the throttle was set at position 4, the total engine power was reduced about 60 brake horsepower and the brake specific fuel consumption was slightly increased.

Reference 2 shows that the maximum above-average temperature of cylinder 10 was about 125° F, whereas cylinder 4 exceeded average temperature by 80° F. Thus no advantage exists in reducing the temperature of cylinder 10 by more than 45° F. A reduction of 45° F would require that throttle position 3 be used, which would reduce the power output of the engine by about 30 brake horsepower for normal rated engine speed and manifold pressure.

Predictions of the effect of any particular intake-pipe throttle setting at engine conditions other than those tested are uncertain inasmuch as it is expected that the effect of the intake-pipe throttle will vary with power and engine speed.

The intake-pipe throttle located in cylinder 10 has no effect on the temperatures of other cylinders (fig. 6).

The intake-pipe throttle will permit higher temperature-limited power under any condition where the temperature of a single cylinder without the throttle is limiting. Under these conditions, it is theoretically possible that the power on the entire engine could be increased approximately 17 times as much as the power lost on the particular cylinder that is throttled. Because of the unavoidable changes in temperature distribution with engine conditions, however, the permissable increase in power is probably much smaller than that theoretically indicated. At conditions that are limited by engine speed and manifold pressure, such as above-critical-altitude and knock-limited conditions, the intake-pipe throttle will reduce the engine output and provide no advantage due to temperature reduction. Cruising economy, unless temperature-limited, would also be little affected by the addition of the intake-pipe throttle.

The result of the climb tests with and without the throttle in the intake pipe of cylinder 10 is shown in figure 7. In this figure are plotted time histories of temperature T35 of cylinder 10 and the important variables affecting the temperature as well as the climb performance. Also shown on figure 7 are the temperatures T12 of cylinder 4 (the second hottest cylinder) taken at intervals during the climb (T35 for cylinder 4 was not recorded during the climb flights). The flight with the throttle was made on a day in which the air temperatures were on the average about 10° F cooler than the day on which the climb tests without the throttle were made. The use of the throttle during climb resulted in cylinder 10 running about 100° F cooler than without the throttle; only about 10° F of this temperature reduction may be accounted for by the cooler day. The use of the throttle showed no effect on the rate of climb. The brake horsepower in the climb with the throttle was slightly higher at low altitudes and slightly lower at high altitudes than in the climb without the throttle. The increase in horsepower is probably due to the slightly higher manifold pressures and lower air temperature, whereas the decrease in power probably reflects the use of the throttle.

At an altitude of about 20,000 feet in the flight without the throttle, the limiting head temperature was reached and it was necessary for the pilot to increase airspeed and reduce the rate of climb. Although the increased airspeed resulted in an increase in cooling-air pressure drop, the temperature of cylinder 10 continued to increase slowly and the climb was discontinued at an altitude of 25,500 feet with cylinder 10 running a temperature of about 510° F. Inasmuch as limiting head temperatures were not encountered when the throttle was used, the climb was successfully made to an altitude of 30,000 feet in a little less than 16 minutes.

The temperatures T12 shown for cylinder 4 (fig. 7), which was the second hottest cylinder under these conditions, indicate that the cooling conditions on the two flights were nearly equal. During the climb with the throttle, cylinder 10 was about 50° F cooler than cylinder 4 (30° F difference shown in fig. 7 plus 20° F difference between the readings of T12 and T35 as indicated in reference 2). This overcooling of cylinder 10 indicates that the throttle should have been set at position 3, which would have reduced the temperature of cylinder 10 to approximately equal that of cylinder 4, the next hottest cylinder.

The results of the climb test indicated that the use of the throttle is practical in that it improves the rate of climb when the conditions are such that the operation is normally temperature-limited. If operation is not temperature-limited, however, the reduction in power due to the use of the throttle does not appreciably affect the rate of climb. If the throttle had been set at position 3 instead of position 4, the temperature of cylinder 10 would still have been below limits and the reduction in power would have been somewhat less as shown from the level-flight test.

Coolant injection. - The results of coolant injection to cylinder 10 are shown in figure 8. The first 14 pounds-per-hour internal-coolant flow to the cylinder had little effect. Further increase of the coolant flow, however, was very effective in reducing the cylinder temperature. At a flow rate of 44 pounds per hour, the rear-spark-plug-gasket temperature T12 and the rear-spark-plug-boss temperature T35 were reduced about 120° F. The temperature at the rear middle of the cylinder head T19 was reduced about 85° F. These temperature reductions were accompanied by a drop in power of 30 brake horsepower. No measurable change in brake specific fuel consumption occurred but brake specific liquid consumption increased about 3 percent. No data were available on the barrel temperatures.

A reduction in the head temperature of 45° F (in which case the temperature of cylinder 10 is reduced to that of the next hottest cylinder) would require a coolant flow of about 28 pounds per hour. This reduction would cause a negligible loss of about 10 brake horsepower and no change in fuel consumption. At this rate of flow a 5-gallon supply of coolant would last over 1 hour.

The coolant injection to cylinder 10 affected only that cylinder (fig. 9(a)). Figure 9(b) shows the effect of an internal-coolant flow of 55 pounds per hour at military power conditions. The flow rate tested was much too high for this condition as it caused cylinder 10 to become the coolest instead of the hottest cylinder.

The use of coolant injection to cool an individual cylinder would necessarily require a control device, either manual or automatic, in order to conserve coolant. Inasmuch as the coolant could be turned off when not needed, it would, except for increase in weight, have no effect on airplane performance for any conditions except temperature-limited conditions. Under temperature-limited conditions, the use of coolant injection would permit the power to be increased.

COMPARISON OF METHODS FOR COOLING INDIVIDUAL CYLINDERS

The use of an intake-pipe throttle and coolant injection may be extended for cooling a group of predominately hot cylinders. If the intake-pipe throttle is applied to a number of cylinders, this method becomes less desirable as there is considerable reduction in power. If the intake-pipe throttle was applied to the two hottest cylinders (10 and 4) of the P-47G airplane, reducing cylinder 10 by 60° F and cylinder 4 by 15° F (reference 2 indicated that cylinder 4 may run as much as 15° F hotter than the next hottest cylinder), the loss of power at normal rated conditions would be about 70 brake horsepower for nontemperature-limited operation. For temperature-limited operation, however, a gain in horsepower would be realized.

The coolant-injection method of reducing individual cylinder temperatures appears to be better than throttling in the intake pipe when it is necessary to apply the method to several cylinders because of the lower loss in power. The primary disadvantage of coolant injection (complicated equipment required) would be somewhat reduced for situations in which a certain portion of the equipment is already installed for some other purpose, as on those airplanes using antidetonation injection equipment. The simplicity of an intake-pipe throttle has the advantage where only one or possibly two cylinders are predominately the hottest cylinders and need to be controlled and where no part of the equipment for coolant injection is already present. These methods are considered only as expedients and are not solutions of the fundamental problem of good temperature distribution.

SUMMARY OF RESULTS

Flight tests of an R-2800-21 engine in a P-47G airplane have shown:

1. Excessive temperatures of cylinder 10 were inherent in the position of cylinder 10 and were not due to the mechanical condition of the cylinder assembly.

2. Excessive individual cylinder temperatures were reduced as much as 90° F with an accompanying loss of 60 brake horsepower by throttling the charge in the intake pipe to the cylinder, or as much as 120° F with a loss of 30 brake horsepower by injecting a liquid coolant (50 percent water and 50 percent ethanol by volume) into the cylinder intake. For operation at temperature-limited conditions, however, a gain in power could have been realized by the use of either method.

3. By use of the intake-pipe throttle, a military power climb was made to an altitude of 30,000 feet at conditions that otherwise would have been temperature-limited.

CONCLUSION

Throttling the charge in the intake pipe is a simpler method than coolant injection into the intake pipe particularly when only one cylinder is considerably hotter than any other. Coolant injection into the individual cylinders is a more efficient method than throttling in the intake pipe and is warranted when several cylinders are to be cooled or when parts of the complex equipment required are already available.

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1. Manganiello, Eugene J., Valerino, Michael F., and Bell, E. Barton: Altitude Cooling Investigation of the Pratt & Whitney R-2800-21 Engine in the P-47 Airplane. I - High-Altitude Cooling Correlation. NACA MR No. E5J11, Army Air Forces, 1945.

2. Pesman, Gerard J., and Kaufman, Samuel J.: Altitude Cooling Investigation of the R-2800-21 Engine in the P-47G Airplane. II - Investigation of the Engine and Airplane Variables Affecting the Cylinder Temperature Distribution. NACA RM No. E6I05, Army Air Forces, 1946.

3. Biermann, Arnold E., Miller, George R., and Henneberry, Hugh M.: Economy of Internally Cooling Only the Overheated Cylinders of Aircraft Engines. NACA MR No. E5G14, Army Air Forces, 1945.

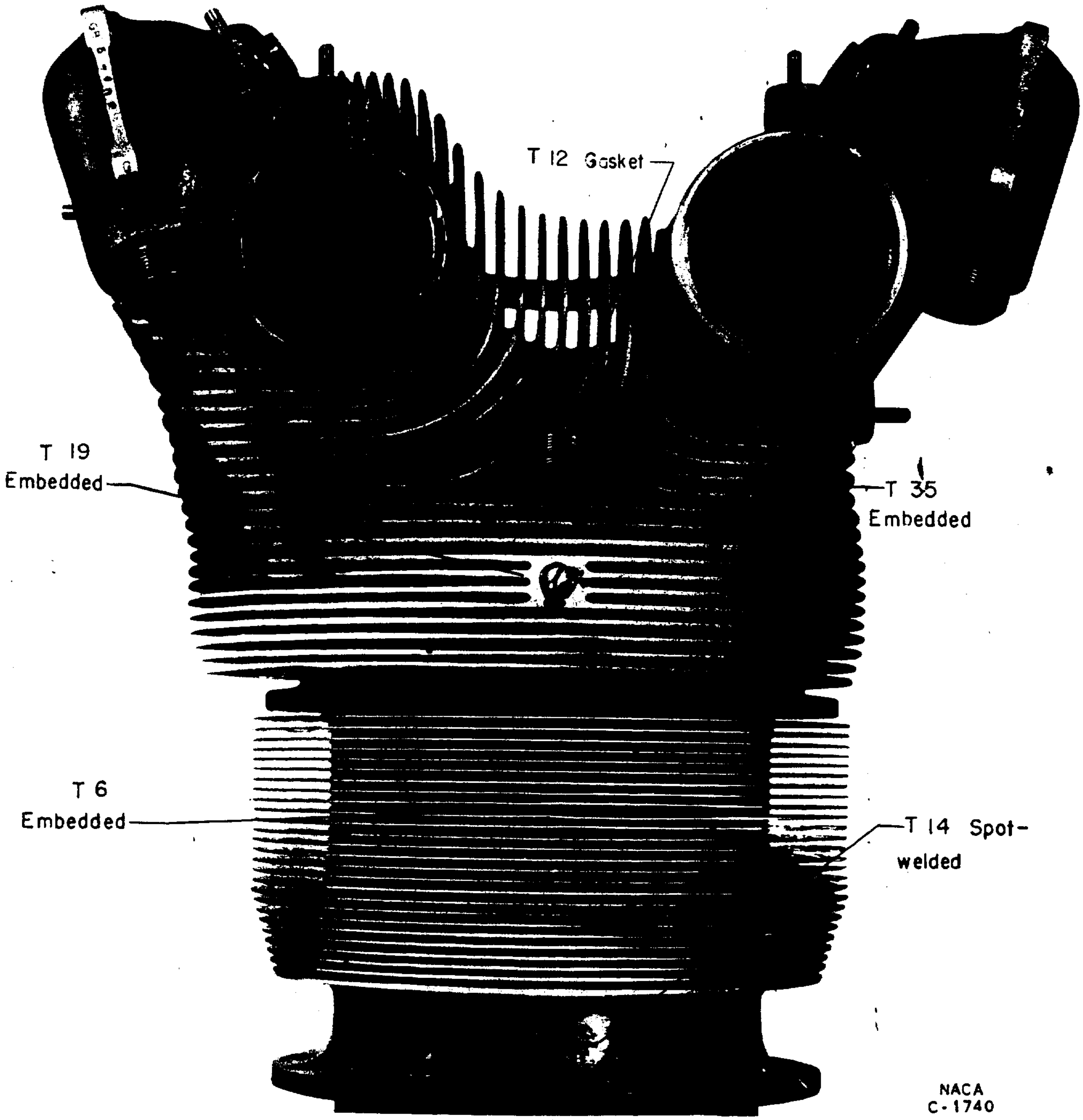
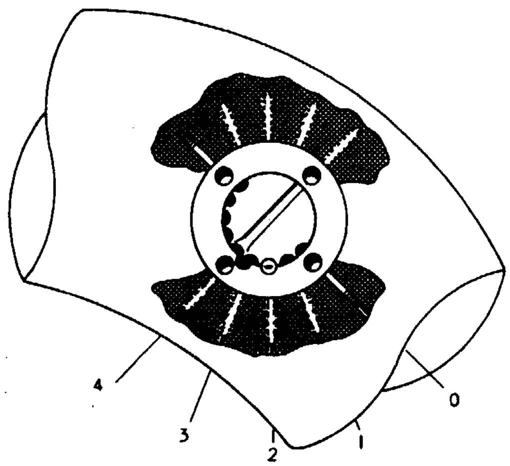
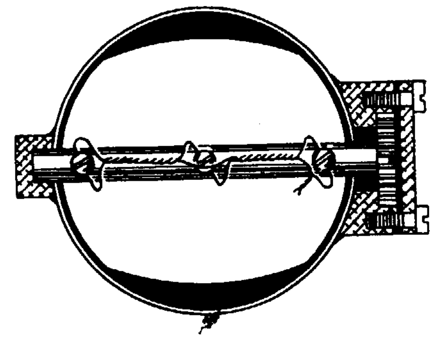


Figure 1. - Rear-view of R-2800-21 rear-row cylinder showing thermocouple locations.



Throttle positions used in tests



Section showing throttle
in position 4

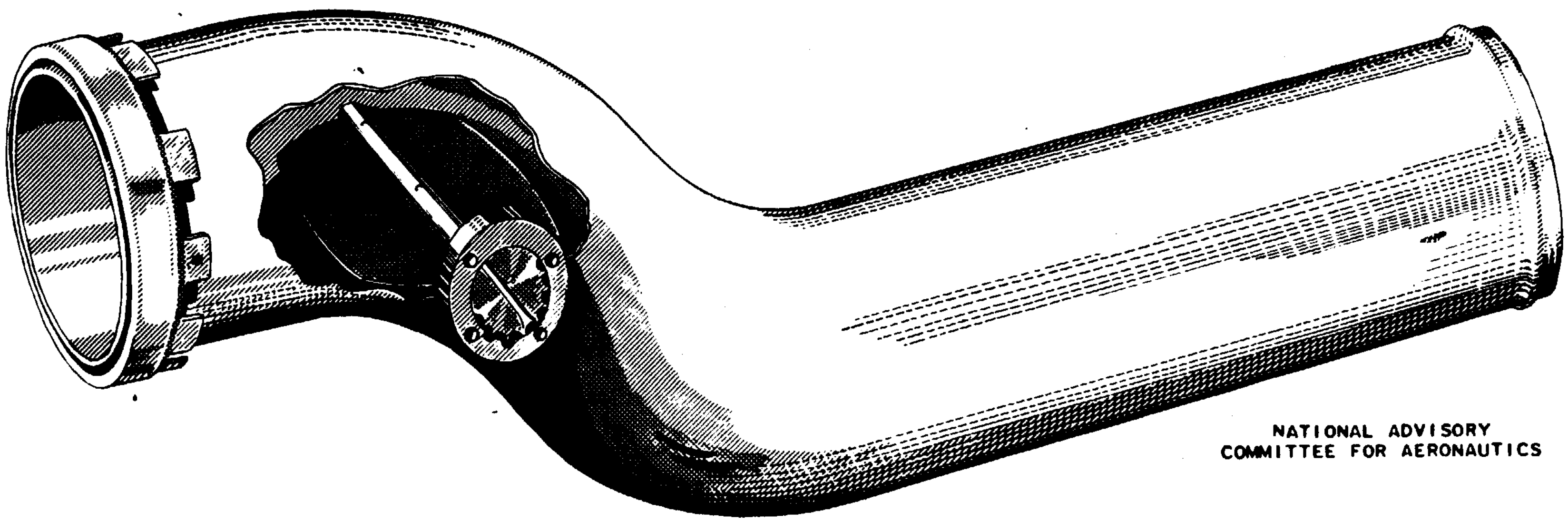


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Figure 2. - Throttle in intake pipe of cylinder 10 on R-2800-21 engine.

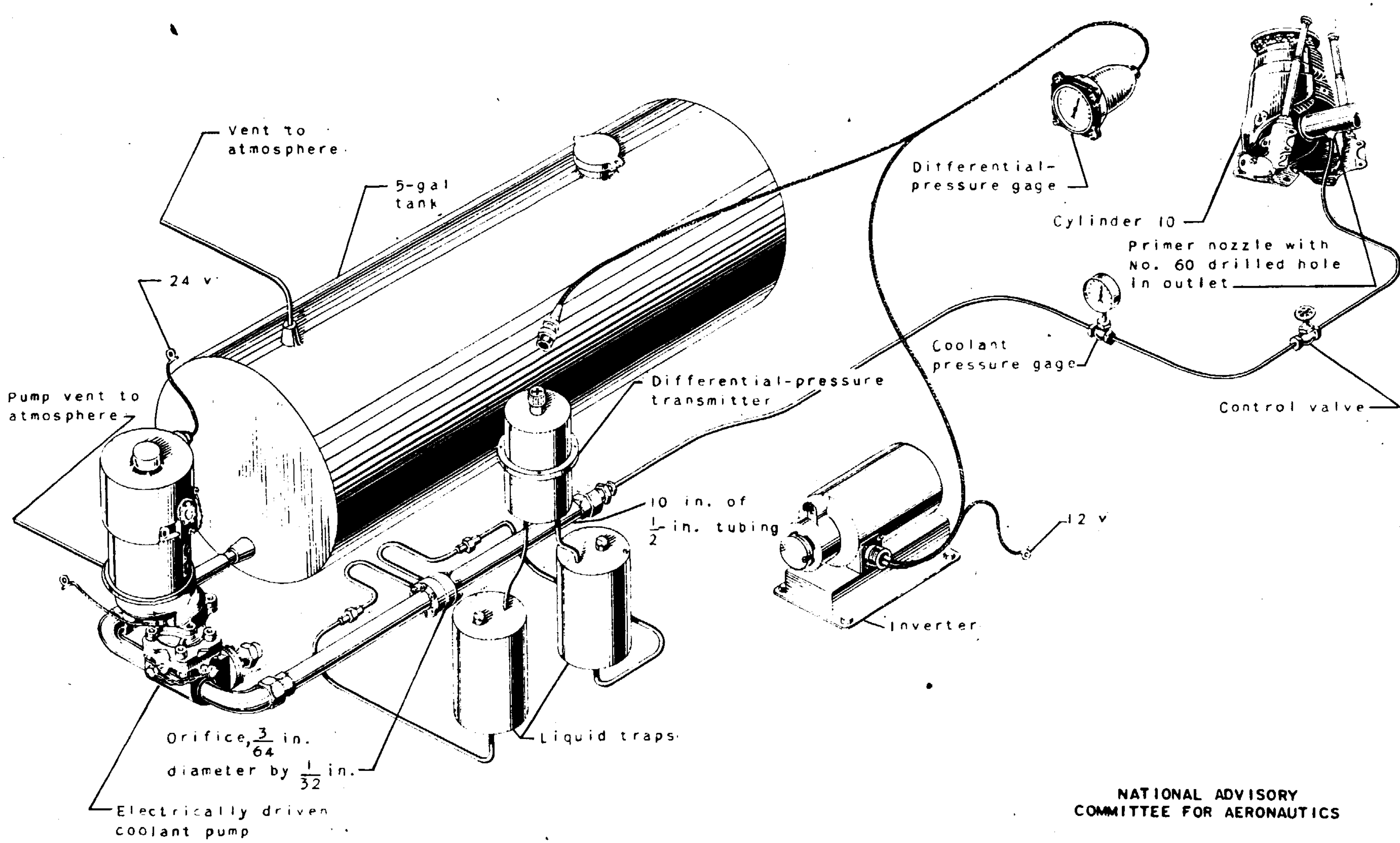

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Figure 3. - Coolant-(water-ethanol) injection system for R-2800-21 engine installation in P-47G airplane.

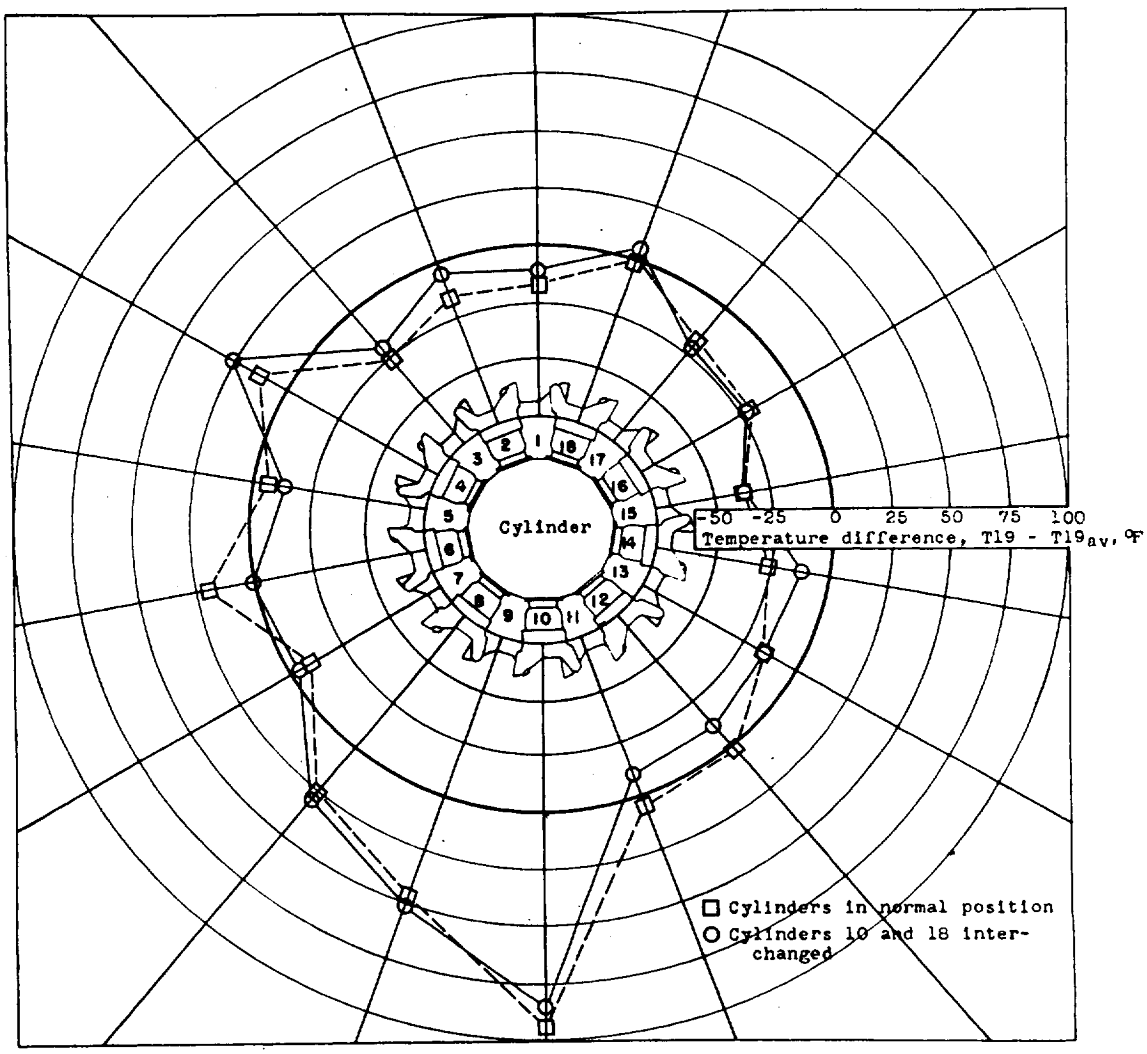

Figure 4. - Effect of interchanging cylinders 10 and 18 on temperature distribution of R-2800-21 engine in P-47 airplane. Engine speed, 2700 rpm; manifold pressure, 49 inches mercury absolute.

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152

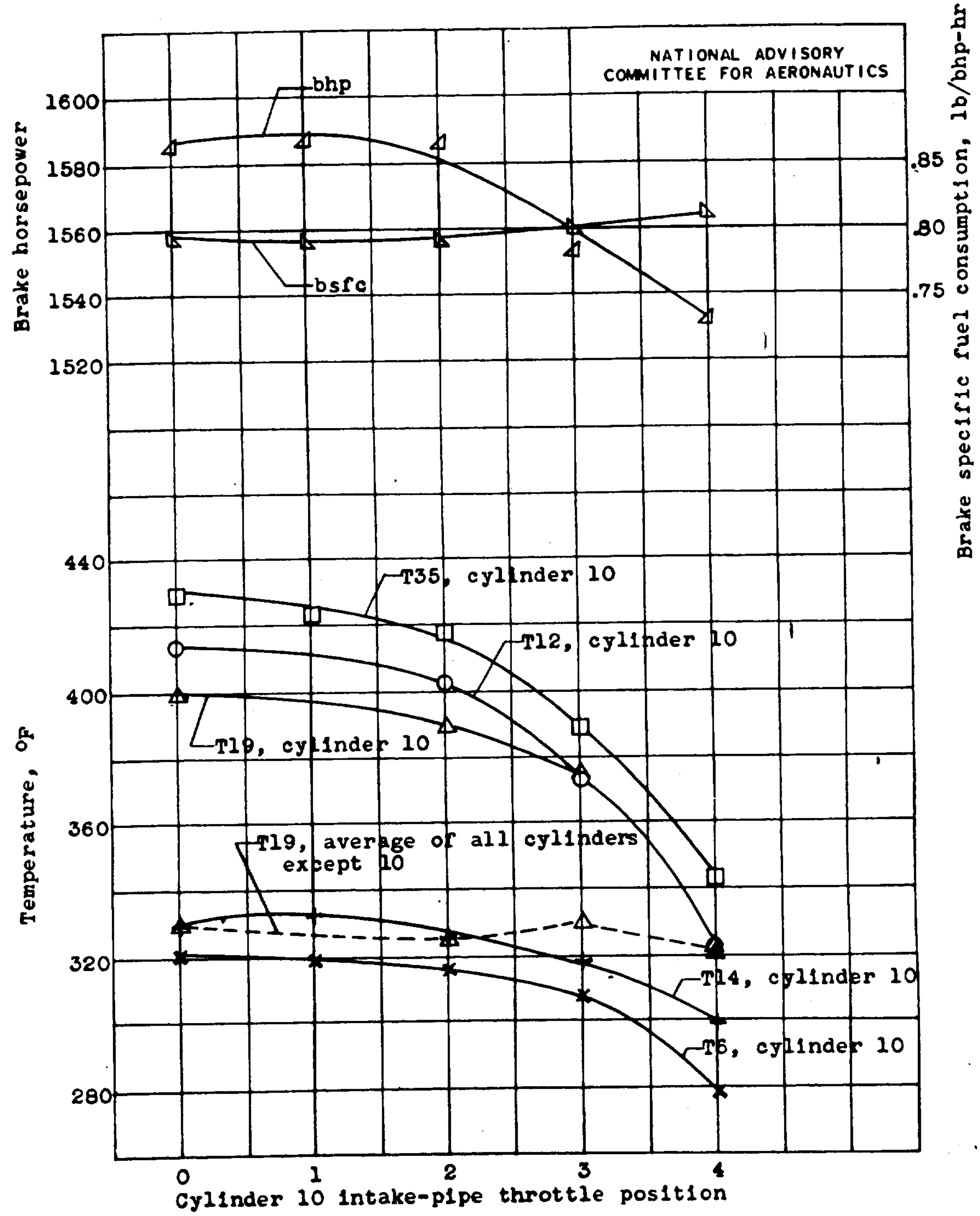

Figure 5. - Effect of cylinder 10 intake-pipe throttle position on engine performance and temperatures of cylinder 10 in R-2800-21 engine. Engine speed, 2570 rpm; manifold pressure, 42.5 inches mercury absolute.

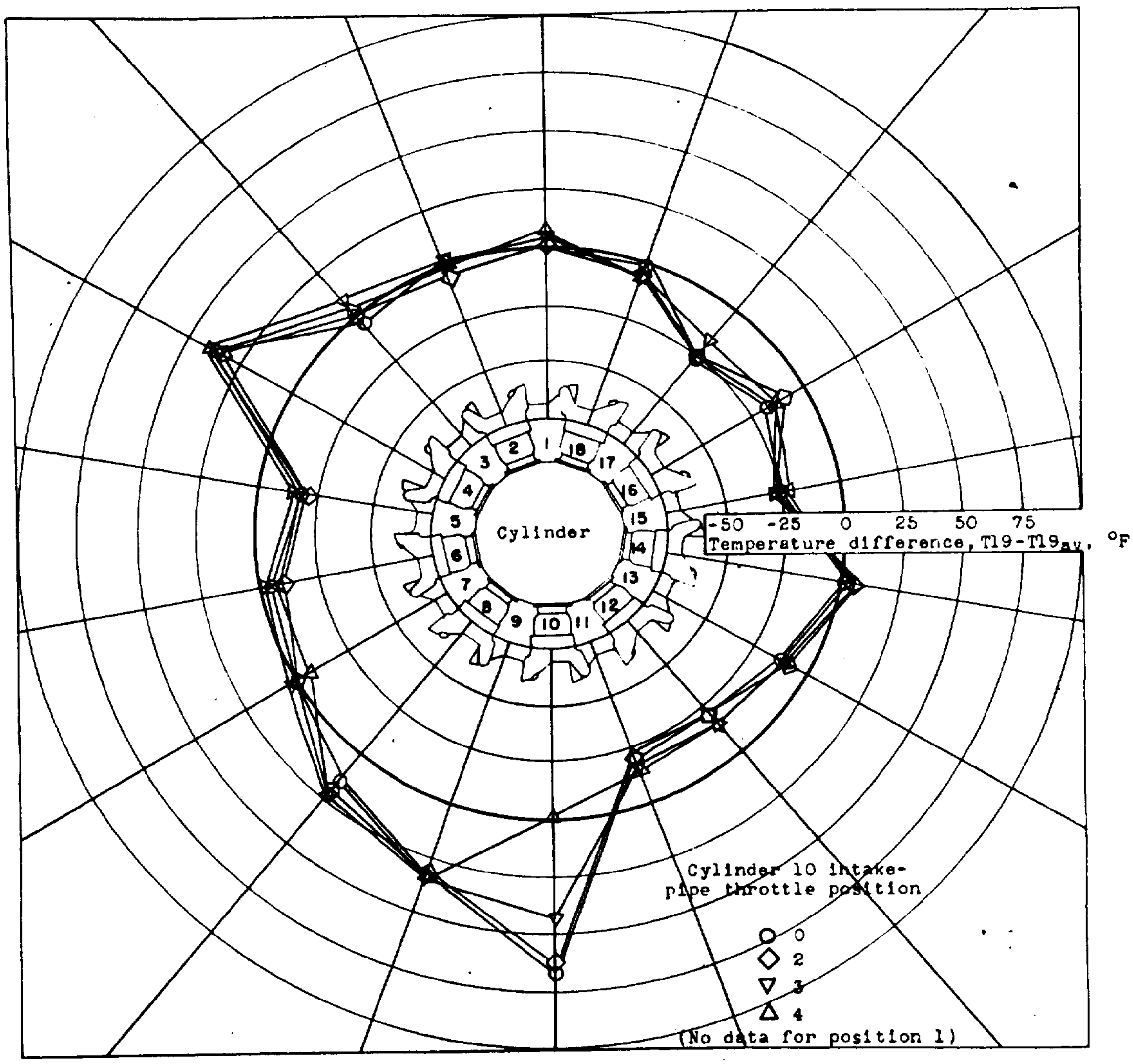

Figure 6. - Variation of cylinder-head temperatures with intake-pipe throttle position in intake pipe of cylinder 10 of R-2800-21 engine in P-47G airplane. Engine speed, 2570 rpm; manifold pressure, 42.5 inches mercury absolute.

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152

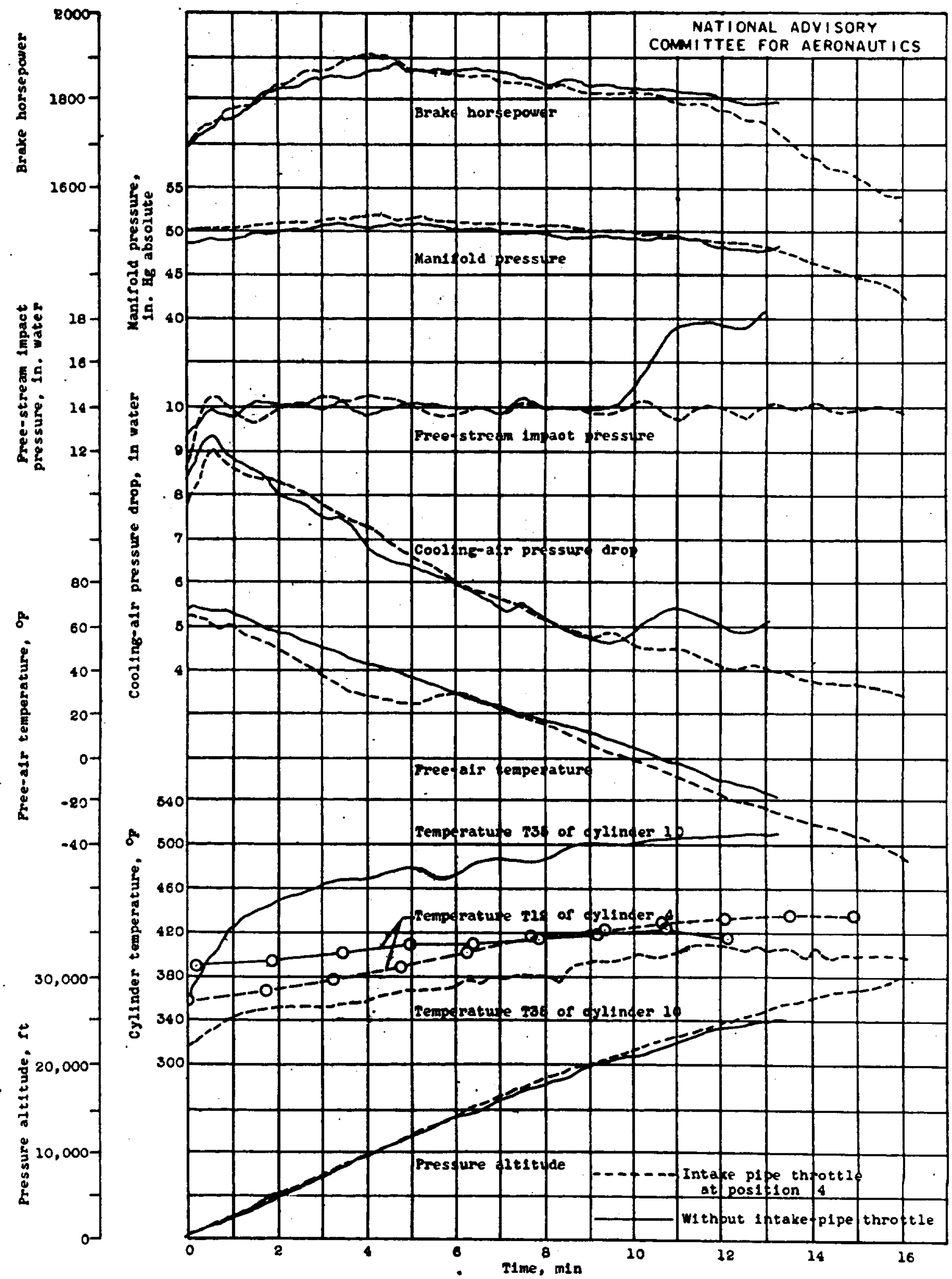


Figure 7. - Effect of intake-pipe throttle on temperature of cylinder 10 and on climb performance of the P-47G airplane equipped with R-2800-21 engine. Engine speed, 2700 rpm; cowl flaps, full open; mixture setting, automatic rich.

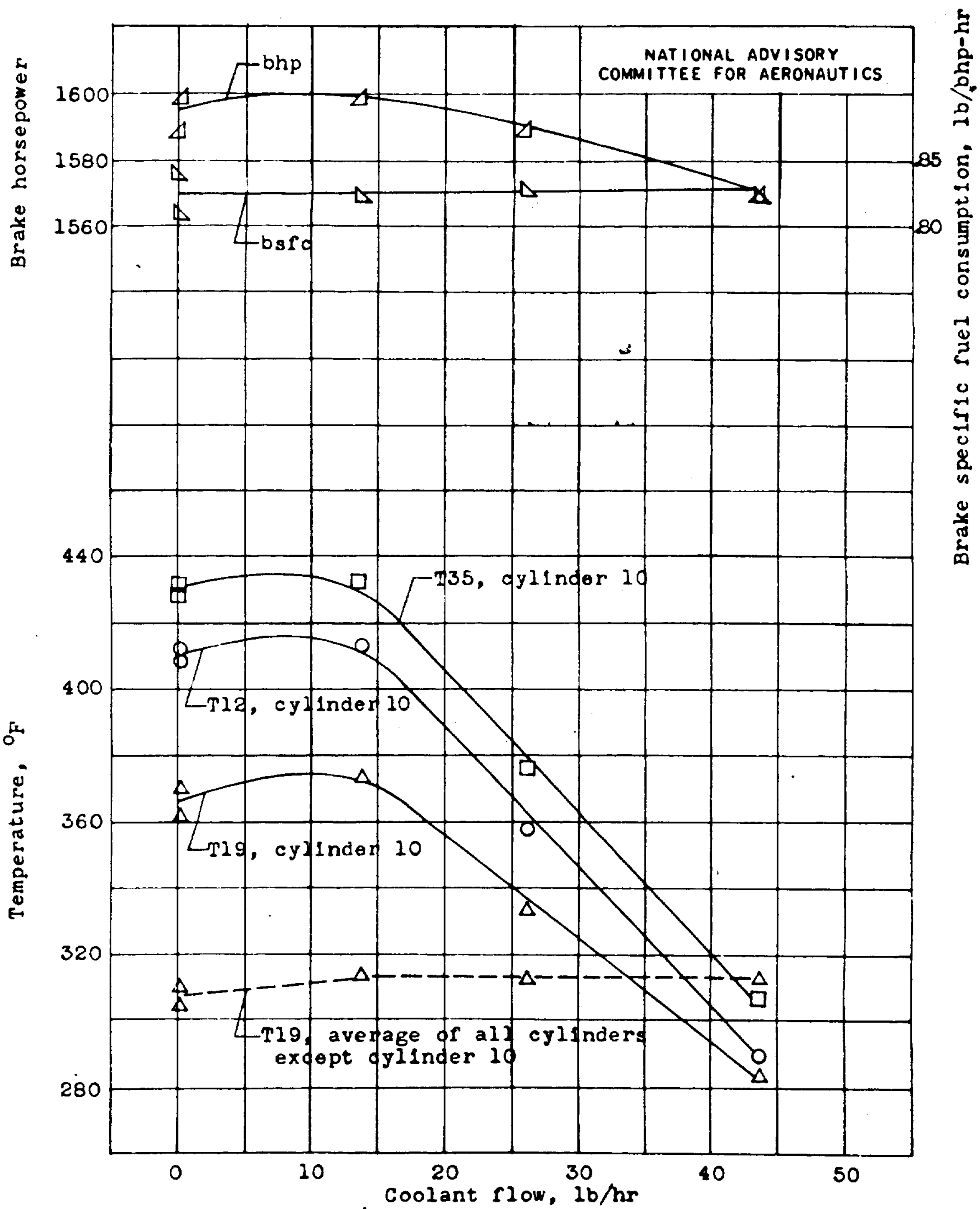
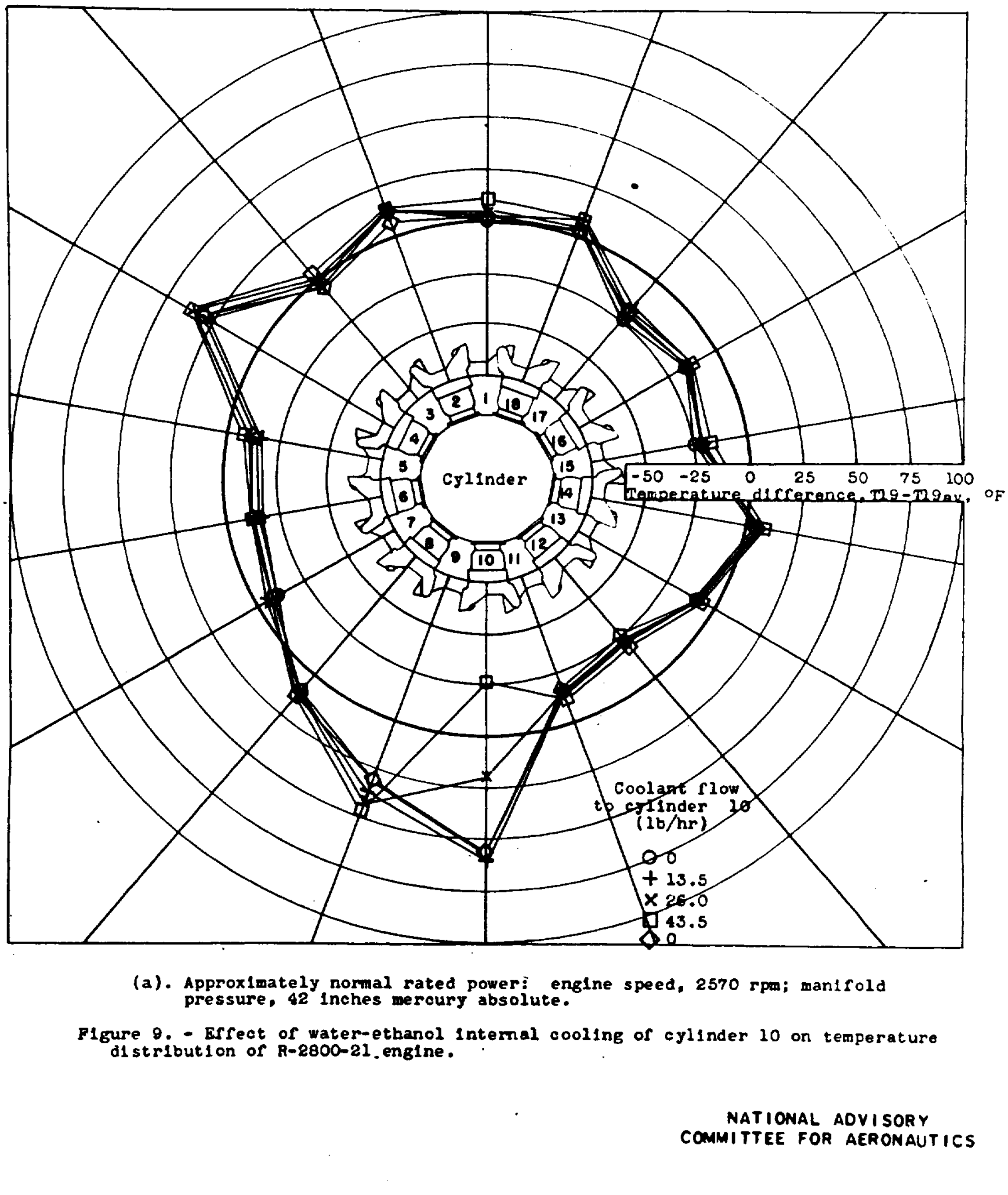


Figure 8. - Effect of coolant flow to cylinder 10 on engine performance and temperatures of cylinder 10 of R-2800-21 engine. Engine speed, 2570 rpm; manifold pressure, 42 inches mercury absolute.



(a). Approximately normal rated power: engine speed, 2570 rpm; manifold pressure, 42 inches mercury absolute.

Figure 9. - Effect of water-ethanol internal cooling of cylinder 10 on temperature distribution of R-2800-21 engine.

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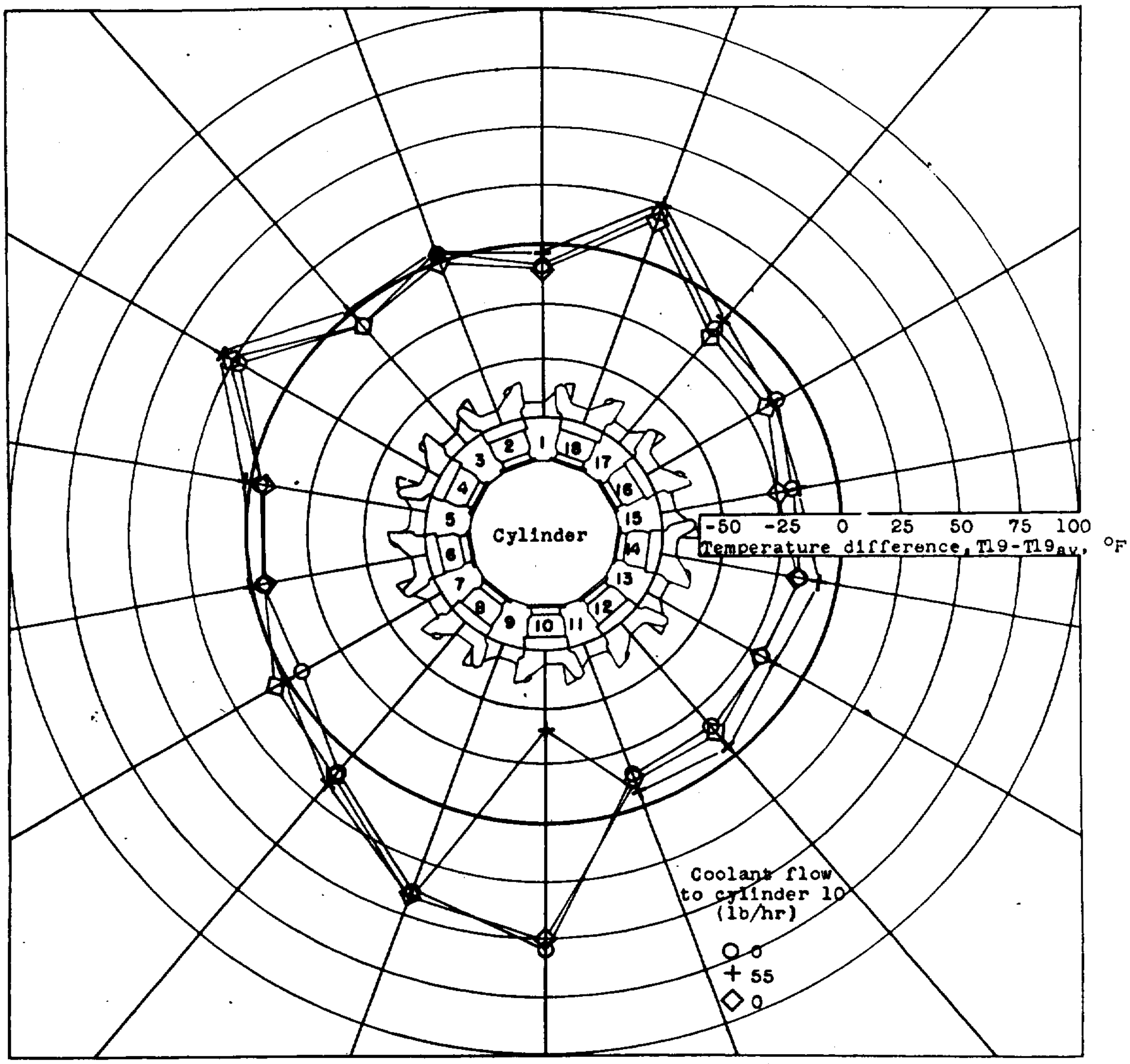

(b). Military power: engine speed, 2700 rpm; manifold pressure, 50 inches mercury absolute.

Figure 9. - Concluded.